

# **HANDBOOK OF NOISE AND VIBRATION CONTROL**

## **CHAPTER 86**

# JET ENGINE NOISE GENERATION, PREDICTION AND CONTROL

D.L. HUFF AND E. ENVIA

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## 1 INTRODUCTION

Aircraft noise has been a problem near airports for many years. It is a quality of life issue that impacts millions of people around the world. Solving this problem has been the principal goal of noise reduction research that began when commercial jet travel became a reality. While progress has been made in reducing both airframe and engine noise, historically, most of the aircraft noise reduction efforts have concentrated on the engines. This was most evident during the 1950's and 1960's when turbojet engines were in wide use. This type of engine produces high velocity hot exhaust jets during takeoff generating a great deal of noise. While there are fewer commercial aircraft flying today with turbojet engines, supersonic aircraft including high performance military aircraft use engines with similar exhaust flow characteristics. The Pratt & Whitney F100-PW-229, pictured in Figure 1a, is an example of an engine that powers the F-15 and F-16 fighter jets. The turbofan engine was developed for subsonic transports, which in addition to better fuel efficiency also helped mitigate engine noise by reducing the jet exhaust velocity. These engines were introduced in the late 1960's and power most of the commercial fleet today. Over the years, the bypass ratio (that is the ratio of the mass flow through the fan bypass duct to the mass flow through the engine core) has increased to values approaching 9 for modern turbofans such as the General Electric's GE-90 engine (Figure 1b). The benefits to noise reduction for high bypass ratio (HPBR) engines are derived from lowering the core jet velocity and temperature, and lowering the tip speed and pressure ratio of the fan, both of which are the consequences of the increase in bypass ratio. The HPBR engines are typically very large in diameter and can produce over 100,000 pounds of thrust for the largest engines. A third type of engine flying today is the turbo-shaft which is mainly used to power turboprop aircraft and helicopters. An example of this type of engine is shown in Figure 1c, which is a schematic of the Honeywell T55 engine that powers the CH-47 Chinook helicopter. Since the noise from the propellers or helicopter rotors is usually dominant for turbo-shaft engines, less attention has been paid to these engines in so far as community noise considerations are concerned. This chapter will concentrate mostly on turbofan engine noise and will highlight common methods for their noise prediction and reduction.

Over the years, aircraft noise reduction research has led to significant progress as indicated in Figure 2, where noise levels from a few representative aircraft/engine combinations are shown using their noise levels in EPNdB (Effective Perceived Noise Level in decibels) as a function of the approximate year they entered service. While some of the noise reduction is due to design changes for engine and aircraft, most of the reduction comes from cycle changes to the engine such as the introduction of higher bypass ratio turbofan engines. Military aircraft are not included in Figure 2 since they are exempt from certification. However, there has been increased sensitivity by the general public to noise from these aircraft near air bases over the past few years. General aviation aircraft and rotorcraft are also not included in Figure 2. In addition to

EPNdB, other metrics such as A-weighted (dBA) noise levels for low altitude flyovers are used. Commercial aircraft use the EPNdB noise metric and distinguish takeoff and approach conditions. The three main certification points are takeoff (also called “sideline”), takeoff with cutback and approach (see Chapter 118 for more information on aircraft noise metrics). The certified noise levels are regulated by organizations such as the Federal Aviation Administration (FAA) in the United States and are recommended by members of the International Civil Aviation Organization (ICAO) to provide international standards. Takeoff noise levels are usually dominated by the engine, while approach levels consist of sources from both the airframe and engine. In fact, some aircraft are dominated by airframe noise sources such as landing gear, flaps and slats during approach. For more information on these noise sources, see Chapter 84.

Aircraft engine noise is primarily an aerodynamic source and is not produced by structural vibration. However, there are some cases, particularly for propeller driven aircraft, where structural vibration from the engines couple with the aircraft structural and acoustic modes in the cabin and cause high levels of interior noise. This distinction has given rise to the term “aeroacoustics” when describing aerodynamically generated noise. Engine noise is principally caused by the interaction of flow’s coherent and random fluctuations (i.e., turbulence) with the aerodynamic surfaces inside the engine producing tonal and broadband components of noise, respectively. It can also be produced by fluctuations in the flow field that radiate sound (such as jet noise). For more information on the fluid mechanics associated with aerodynamic noise, see Chapter 7.

## 2 ENGINE NOISE SOURCES

The major noise sources for a modern turbofan engine are shown in Figure 3. The relative sound levels from each component depend on the engine architecture and power setting. At takeoff condition, the fan and jet noise usually dominate. For approach condition, the fan usually dominates since the jet velocity is reduced. Noise from other components such as the compressor, combustor and turbine is generally less than the fan and jet. This is why most of the noise reduction research over the past 25 years has emphasized fan and jet noise reduction. The inlet noise includes the contributions from both the fan and compressor, but is primarily dominated by the fan. Aft radiated noise is dominated by the fan and jet, but there can also be significant contributions from the combustor and turbine which are highly dependent on the particular engine. The noise levels shown in Figure 4 represent an average from engines that were available in 1992 that powered a medium sized twin engine aircraft such as the Boeing 757 or 767 (nominally 400,000 lbs takeoff gross weight with 60,000 lbs thrust from each engine). Engine component noise levels are also available for other aircraft types like small business jets, small twin engine aircraft such as the Boeing 737, and large four engine aircraft such as the Boeing 747<sup>1</sup>.

Typical radiation patterns (called source directivities) from various engine noise sources are shown in Figure 5. Source directivity depends on the engine architecture, power setting and noise source. Directivity can be used as a criterion to select only those engine noise sources that contribute to the community noise metrics. For example, tones from the turbomachinery can be analyzed using modal decomposition and expressed in terms of their “cut-off ratio”. The cut-off

ratio is a measure of how well a mode can propagate inside the engine duct. Highly cut-on modes tend to radiate along the axis of the engine (both upstream and downstream) and do not impact the community since they are directed away from the ground and attenuate through the atmosphere. On the other hand, modes that are just cut-on propagate 90 degrees from the engine axis and acoustic treatment in the nacelle is most effective since the sound waves propagate directly into the liner. Modes that propagate from 30 to 60 degrees from the forward engine axis are the most difficult to control. The use of modal analysis to characterize turbomachinery tones was pioneered by Tyler and Sofrin<sup>2</sup> and is still used today to understand engine noise sources.

### **3 NOISE REDUCTION STRATEGIES**

Most of the engine noise reduction advances have come from changing the engine cycle and incorporating low-noise technologies. During the 1960's and 1970's, low-noise design guidelines were developed: eliminating inlet guide vanes in front of the fan, incorporating acoustic liners in the fan duct and the core, increasing the spacing between rotors and stators, using lobed mixers on the exhaust, and developing "wide-chord" fans with lower tip speeds. Many of these advances have dual benefits for reducing noise and increasing the propulsive efficiency. Some of the techniques that have been developed over the past 25 years are highlighted for each engine component below.

#### **3.1 Fan Noise**

Fan noise research requires simulation of conditions representative of the engine operating during takeoff and approach. Static tests use an Inflow Control Device (ICD) mounted on the inlet that resembles a large mesh golf ball that is much larger than the diameter of the fan. It was discovered during the 1970's that running a fan without flow conditioning caused large scale turbulence and ground vortices to be ingested into the fan producing extraneous fan noise in the process. The purpose of the ICD is to break up the turbulence into small eddies that decay to levels representative of atmospheric turbulence entering the fan. Unfortunately, many good noise reduction ideas tested before this discovery were prematurely discarded because of contaminated data. An alternate approach is to run the fan in a wind tunnel with appropriately low levels of free stream turbulence to simulate the forward flight conditions. If the wind tunnel is large enough, angle of attack simulations can also be done to make sure inflow distortions into the fan are not a major noise source.

Since it is difficult to extract the fan noise from engine spectra that contain other sources, most of the research on fan noise is done in fan rigs where the source can be isolated. Results from decades of tests have shown that fan tip speed and pressure ratio control the overall fan noise levels. For subsonic tip speeds, the interaction of fan wakes with the stators is the dominate source. This dependence has been demonstrated in recent "source diagnostics tests" at Boeing and the NASA Glenn Research Center.<sup>3-4</sup> Methods for reducing this noise at the source include decreasing the fan tip speed, reducing the fan pressure ratio, increasing the fan/stator spacing,<sup>5</sup> sweeping and leaning the stators to reduce tones,<sup>6-7</sup> selecting favorable fan blade/stator vane ratios to reduce the tones<sup>5</sup>, and reducing the number of stators to reduce the broadband noise.<sup>3,4</sup> For supersonic fan tip speeds, the self noise generated by the fan becomes an important



contributor, especially for inlet radiation noise. With the exception of Multiple Pure Tone (MPT) noise, less is known about the source mechanisms associated with the rotor self noise since noise measurements are typically dominated by rotor-stator interaction sources. Special experiments have been done to help isolate this source,<sup>3-4</sup> but no noise reduction strategies have been successful beyond tip speed and pressure ratio changes (aerodynamic loading).

Multiple Pure Tones or “buzzsaw” noise is also associated with the rotor operating at supersonic tip speeds. This source is due to small blade-to-blade geometric differences (e.g. stagger angle) that cause the shocks on each blade to have a unique propagation characteristic upstream of the fan. Depending on the particular fan, tones at multiples of the shaft order frequencies can be heard in the far field as the aircraft approaches an observer. Noise reduction methods for this source include re-arranging the fan blades on the fan disk to modify the frequency content, using tighter manufacturing tolerances to minimize blade-to-blade differences, optimizing acoustic treatment in the inlet to absorb these tones, or using blade sweep to reduce the strength of the blade shocks and capture the associated normal shocks inside the fan blade passages.

Another fan noise source is the interaction of inflow distortions or inlet surface boundary layers with the fan. This source is believed to be secondary for well designed nacelles where inflow distortions and boundary layers are minimized for performance and operability reasons. Depending on the diffusion downstream of the inlet throat and the tip clearance between the fan case and the fan tip, the boundary layer on the inlet may not interact with enough of the fan blade span to be a major noise source.

Acoustic treatment is used in turbofan engines primarily to reduce turbomachinery noise from the fan, compressor, or turbine. Since the liners need to endure harsh environments (high temperature, cyclic weather conditions including ice and jet fuel byproducts), materials are limited and often not optimal for maximum noise reduction. Liners usually consist of a face sheet with porosity to provide desired resistance without significantly increasing the skin friction. Sometimes a fine wire mesh is used in place of the porous face sheet. The face sheet covers cavities that are sized to provide the desired impedance over a range of frequencies for noise attenuation. Metal honeycomb is a common structure for the cavities. In some applications, multiple layers of liners are used that are designed to different peak attenuation frequencies to provide a wider bandwidth of suppression. Single, double, and sometimes triple degree of freedom liners are used in modern engines. Cost and weight are also factors considered for liner selection. It is most common to use acoustic liners in the fan inlet and the bypass duct downstream of the fan on both the nacelle and the core cowl. The design of a liner starts with determining the ‘hard-wall’ (no acoustic treatment) spectra and choosing a frequency range where attenuation is needed. It is best to use a PNL weighting (Chapter 118), which usually targets 2 to 4 kHz. Recent improvements in manufacturing methods have helped minimize the splices associated with the circumferential segments that make up the liner. The splices cause a spatial discontinuity of the acoustic impedance that could cause the fan noise to increase. Reducing the number of splices and circumferential extent of the splice increases the effectiveness of the liners. Higher bypass ratio engines have shorter inlets and nacelles to minimize aerodynamic drag, which compromises the available treatment area. So even though higher bypass ratio engines are quieter at the source, acoustic treatment can be less effective due to less treatment area.

To overcome the problem, several alternate methods have been developed recently such as scarf inlets and active noise control. Scarf inlets resemble a sugar scoop in that the lower lip extends further upstream than the top of the inlet. This redirects the inlet radiated fan noise away from the ground. Acoustic treatment is used to absorb the acoustic rays that impact the sound levels on the ground. While this idea was first developed in the 1970's, only recently modern Computational Fluid Dynamic (CFD) methods have provided improved aerodynamic prediction methods to help make scarf inlets more practical. Boeing has developed a scarf inlet that integrates acoustic treatment to optimize the inlet for lower noise.<sup>8</sup> Despite these advances, scarf inlets have not yet entered service.

Active noise control is still in its infancy for turbofan applications. While, it has been successful in mitigating noise in simple configurations, such as plane waves in a ventilation duct, the application of active noise control to turbofans have proven to be very challenging. This is primarily because of the complexity of the source which typically consists of many circumferential and radial modes for even a single tone. Nonetheless, over the past ten years, active noise control research has made significant strides (in idealized configurations), progressing from single frequency/mode cancellation to multiple frequency/mode cancellation involving both the inlet and aft radiated fan noise. A typical active noise control system consists of ring(s) of actuators to provide the cancellation source, a set of error microphones to monitor the cancellation level, and a control algorithm to provide real-time optimization of the noise cancellation. (A summary of active noise control systems is included in Chapter 59). The source actuators have been placed in various locations of the inlet and aft fan duct, and sometimes imbedded in the acoustic treatment. One test<sup>9</sup> performed by BBN and NASA used actuators embedded in the stators to provide more control over the radial spinning modes (Figure 6). However, the number of error microphones and source actuators needed to reduce complex fan noise sources (especially at higher frequencies) is too large for practical applications. In addition, the actuators need to be robust, produce high amplitude sound output, and be effective over a range of frequencies. Creative ways to reduce the system requirements and cost are needed to make active noise control feasible for aircraft engines. Another strategy for active noise control is to integrate it with the acoustic treatment to make the liners more effective. A hybrid active/passive approach has been developed by Northrop Grumman.<sup>10</sup> A summary of active noise control research for fans can be found in an article by Envia.<sup>11</sup>

### **3.2 Jet Noise**

Jet noise reduction research is also typically done in model scale rig tests. This noise source is distributed across the jet plume and is responsible for the low frequency rumble that can be heard as the aircraft is flying away from an observer. Since most of the noise is generated external to the engine, noise reduction methods are difficult to implement. It is important to simulate forward flight effects when evaluating jet noise reduction concepts since the strength of the shear layers from the exhaust nozzles vary with forward flight speed. Reduction methods that work well for static tests often have a reduced benefit when forward flight simulations are included. Many engine noise tests are done on static test stands, which require corrections for jet noise using either model scale data that includes forward flight or correlations based on previous experience. This raises the level of uncertainty and sometimes leads to incorrect jet noise

assessments. Another major consideration is running the jets at realistic temperatures. Cold jets display different characteristics in the noise spectra than hot jets and noise reduction concepts need to work for a range of operating conditions.

The major parameter controlling jet noise is the exhaust velocity gradient. The common rule of thumb holds that the jet noise varies with the velocity raised to the eighth power for jets with subsonic flows. This was first derived by Lighthill.<sup>12</sup> For a single-flow, round jet with subsonic exhaust velocities, the jet noise spectra consists of broadband noise with a peak frequency scaling with the Strouhal number ( $fD/U$ , where  $f$  is the frequency,  $D$  is the jet diameter, and  $U$  is the fully expanded jet velocity). The most common and effective way to reduce jet noise is to simply reduce the exhaust velocity. For higher bypass ratio turbofans, the core stream velocity is reduced as more energy is extracted from the turbine. This reduces the velocity gradients between the core and the bypass streams and between the fully mixed jet and the ambient air.

There are two basic types of exhausts on turbofans: internally mixed, where the core flow mixes with the bypass flow inside the nacelle, and separate flow nozzles, where the flows mix downstream of the nacelle exit plane. Lobed mixers are used for internally mixed engines to provide both noise reduction and performance benefits. They resemble cookie cutters located at the core nozzle exit. The purpose is to mix the flow streams in a way that lowers the “mixed” velocity exiting the engine without introducing additional turbulence that causes high frequency noise. It also provides a favorable static pressure and temperature profile at the exit that can improve the engine thrust. Many experiments have been carried out that investigate different mixer designs by varying the penetration of the lobe into the bypass and core flows, the number of lobes, and the shape of the lobes. CFD methods are now able to aid the design of complex non-axisymmetric mixers. While the performance assessments are fairly reliable, the link to noise generation and propagation is still a research topic. The optimum mixer design is dependent on the engine configuration and operating parameters. It is difficult to derive general noise reduction design guidelines other than being careful not to mix the flow so aggressively that high frequency noise generation penalty negates the low frequency noise reduction benefit. In some applications, acoustic treatment is added to help absorb this high frequency noise if it is generated inside the engine. Generally speaking, mixer designs with good aerodynamic performance (mixing with low losses) are good acoustic designs.

Separate flow nozzles are common on larger engines. Until recently, there were no noise suppression methods implemented on engines for reducing the jet noise from these exhausts systems. In 1996, NASA worked with several U.S. companies to investigate the use of tabs and chevrons to mix the core and bypass flow streams for jet noise reduction. Chevrons, which resemble a saw tooth pattern on the trailing edge of the nozzle (Figure 7), were found to reduce the jet noise by about 3 EPNdB without significant thrust loss. (The success of all engine noise reduction methods are based on the amount of noise reduction that can be achieved without significant thrust loss). Similar to the internal mixers, the key to this application is providing just enough mixing of the flow streams to impact the turbulence in the jet without increasing the high frequency mixing noise. The penetration of the chevrons into the core and bypass flow is small, but sufficient enough to generate stream-wise vorticity into the shear layer which reduces the velocity gradients in the plume. Over the past few years, chevrons have been introduced on new engines such as General Electric’s CF34-10. Proceedings from a jet noise workshop sponsored



by the AeroAcoustics Research Consortium (AARC) provide a good overview of recent progress in jet noise control and prediction.<sup>13</sup>

### **3.3 Compressor Noise**

There has not been much research done on compressor noise for many years. If it is a problem, it is usually identified as tones radiating from the inlet. These tones are easily identified using narrowband spectra in the far field knowing the shaft rotational speed and the number of rotor blades in the compressor stages (blade passing frequency = number of blades x fan RPM / 60). For compressors, rotor-stator interaction is the dominant noise source, especially due to the close rotor/stator coupling which may excite the potential field interaction between the adjacent blade rows in addition to the viscous wake interaction. The interactions are also more complex than the fan since multiple stages are involved. The blade passing frequencies and higher harmonics associated with each blade row create many tones in the spectra. Fortunately, transmission losses across the rotors and stators block the radiated noise from the stages deeper in the engine core. Attention is usually given to the first one or two stages that do not get this benefit. The blade/vane ratio and tip speeds are carefully chosen to take advantage of cutoff using the theory of Tyler and Sofrin.<sup>2</sup> Another strategy is to select blade and vane numbers that produce counter rotating circumferential modes that are more efficiently blocked by upstream blade rows (the acoustic waves tend to hit the blades broadside and reflect rather than being transmitted through the blade row).

### **3.4 Combustor Noise**

In modern turbofan engines, combustion noise is usually the lowest priority for noise reduction. Most of the research that was done in the 1970's is still used today to understand this source and provide design guidelines. Combustion noise propagates through the turbine stage(s) and peaks at downstream angles centered around 120 degrees from the inlet axis, and has a broadband character that peaks anywhere from 400 to 600 Hz. It is sometimes hard to distinguish this source from the jet noise. Combustion noise is usually most apparent at low engine power settings such as idle. As the engine speed increases, the combustion noise becomes masked by the jet noise. Cross correlation techniques using unsteady pressure measurements in the combustor, turbine exit, and far field have been used with limited success to identify this source. Examples of combustion noise reduction methods include increasing the number of fuel nozzles in the burners, decreasing the fuel/air ratio, decreasing the burner pressure, and decreasing the flow through the combustor.<sup>14</sup>

### **3.5 Turbine Noise**

The character of turbine noise is similar to compressors in that it is mostly tones radiating from the multiple stages of the turbomachinery. The tones radiate aft through the shear layer between the core and bypass streams. This causes the tones to scatter into adjacent frequency bands and appear as haystacks when measured in the far field. Since there can be many tones, even with narrowband analysis this source may appear as broadband noise. It is also difficult to distinguish aft radiated fan noise from turbine noise. A common diagnostic technique is to use acoustic treatment in the tail-cone near the turbine exit and compare the spectra with the total spectra

from the engine over a range of speeds. Noise reduction concepts are challenging since the engine cores need to be compact to reduce engine weight making less room available for conventional noise reduction approaches. Modern turbofans use fewer stages in both the compressor and turbine components with increased aerodynamic loading on the blades, which can increase the noise. Common noise reduction concepts include selecting the blade numbers and rotational speeds for cut-off or increased transmission loss<sup>15</sup>, and using acoustic treatment. Engines that can run the turbines at higher rotational speeds benefit from placing the tones at frequencies that are high enough to be less annoying.

## **4 ENGINE NOISE PREDICTION METHODS**

In order to predict the noise from an engine, one must predict the noise from its constituent components, namely, fan, jet, compressor, combustor and turbine. Once the noise levels from individual components are predicted, they can be combined in a judicious manner to develop a system level noise prediction for the engine. The current state-of-the-art in the engine system noise prediction capability is exemplified by the ANOPP code<sup>16</sup> which actually includes provisions for both the engine and airframe. In its current form, the engine noise modules in ANOPP are empirically-based owing the complexity of the sources involved, but eventually it is hoped that those modules would be replaced by more sophisticated physics-based prediction capabilities. In the following sections an overview of the methodologies being used (or developed) for predicting noise from the various source of engine noise is given.

### **4.1 Fan Noise**

Fan noise prediction methods can be grouped into three broad categories: empirical, analytical and computational. In the first category methods, of which Heidmann's<sup>17</sup> is a good example; experimental data are used to construct correlations between appropriate fan noise metrics and operating parameters. Typically the chosen noise metric is the EPNdB and the operating parameter is either the fan tip speed or its pressure ratio. The correlations are often constructed for overall fan noise levels, but improved results might be obtained by developing separate correlations for each of the contributing sources of fan noise (see earlier discussion). While it takes experience and skill to discern the appropriate correlation relationships, once constructed these methods are easiest to use. The main shortcoming of the empirical methods is that their applicability is limited by the range of data used to construct the correlations. As a result, they cannot be reliably used to predict noise when the fan design and/or operating conditions lie outside of the envelope of the databases used to construct the correlations. These methods are widely used, principally as part of system level prediction codes for engine design evaluation studies.

As the name suggests, the methods in the second category are analytical in nature relying on first principles as well as phenomenological considerations of the noise generation and propagation processes. Most of the methods in this category are based on the Acoustic Analogy theory developed by Lighthill.<sup>12</sup> In Acoustic Analogy, the aerodynamic and acoustic aspects of the problem are treated separately. Mathematically, this is done by a rearrangement of the exact

equations of the motion so that a wave equation is obtained whose left hand side describes the propagation and refraction of sound and its right hand side represents a “known” aerodynamic source that generates the sound. The aerodynamic source is to be measured, computed or otherwise modeled independently. The solution to the wave equation is given formally in terms of integrals that describe convolution of the source distribution and propagation characteristics. Depending on the level of approximations involved in the description of the fan geometry and/or flow conditions, the solution can be expressed either in closed form, or may require the use of quadrature schemes to evaluate the solution integrals. The overall fidelity of these methods is predicated on the level of approximations used to describe the source(s), the fan geometry and flow conditions. Many examples of analytical methods exist, among them that developed by Ventres et al.<sup>18</sup> It should be noted that when very simple descriptions of fan geometry and flow conditions are used (i.e., flat plate blades and uniform background flow), the aerodynamic and acoustic aspects of the problem can be combined into a single problem and solved simultaneously. Examples of such methods include one developed by Hanson.<sup>19</sup> The analytical fan noise prediction methods can often be used to predict the trends, but they cannot be reliably used to predict the absolute levels correctly. A good example of a fan noise prediction code in this category is called “V072”<sup>20</sup> which is used to predict tone levels produced as a result of the interaction between the fan wakes and fan exit guide vanes.

The third category of fan noise prediction methods encompasses those approaches that, like the analytical methods start with the equations of motion, but make little or no approximations regarding the fan geometry or flow conditions. The resulting coupled system of unsteady flow equations, therefore, retain their complexity and can only be solved numerically through the use of appropriate computational algorithms. These methods, generically called Computational AeroAcoustics (CAA) methods<sup>21</sup>, include linearized frequency-domain methods (e.g., LINFLUX<sup>22</sup>) on the one end of the modeling spectrum and nonlinear time-domain methods (e.g. BASS Code<sup>23</sup>) on the other. If in addition to sound, the flow turbulence is also to be predicted, the computational complexity grows significantly. Depending on the range of turbulence scales to be computed directly, the calculation is referred to as Unsteady Reynolds Averaged Navier-Stokes (URANS), Large Eddy Simulation (LES), or Direct Numerical Simulation (DNS). The latter approach can be used to compute the unsteady flow down to the smallest turbulence eddy sizes where viscosity converts the kinetic energy to heat. While the application of LES and DNS methods for predicting noise from realistic fan configurations is still years away, with recent advances in computer hardware and computational algorithms, the CAA methods that compute only the sound field (like LINFLUX) are beginning to take their place in the “tool box” of fan noise prediction methods. Figure 8 shows a comparison of the predicted and measured modal acoustic power levels for two different stators. The V072 code predicts the change in the total power from one stator to the other accurately, but fails to predict the modal distribution correctly. The LINFLUX code on the other hand, predicts both the trends and absolute levels rather well.

## 4.2 Jet Noise

Jet noise prediction methods can also be grouped into the same three categories as for fan noise. The empirical methods, like the SAE,<sup>24</sup> JEN6,<sup>25</sup> StoneJet,<sup>26</sup> and Fisher & Morfey<sup>27</sup> rely on correlations between the noise level (typically third-octave sound power level) and such jet parameters as the nozzle diameter, exhaust velocity, and exhaust temperature.



Correlations are typically developed for round single-stream cold jets, so more complicated jet configurations (e.g., hot, multiple-stream, non-axisymmetric, non-concentric, etc) are represented by a round jet with equivalent velocity, temperature and diameter. Methods like the SAE make no distinction between the various noise-producing regions of the jet, while others (like StoneJet) divide the flow field into regions with different source characteristics. Due to the differences in the principal mechanisms involved, there are separate correlations for subsonic and supersonic jets. As in the case of fans, the empirical jet noise prediction methods are widely used as design evaluation tools.

Most widely used analytically-based jet noise prediction methods are based on a variant of the Acoustic Analogy theory due to Lilley,<sup>28</sup> which accounts for sound refraction due to background flow non-uniformities as part of the wave operator. A notable exception is the JET3D code<sup>29</sup> which uses Lighthill's original theory. As in the case of the fan, the aerodynamic source of jet noise must be calculated separately. This is usually done through the use of CFD which provides both the background flow through which sound propagates and refracts, and the source strength distribution in the form of intensities and integral time and length and scales of turbulence. The most widely known example of these methods is the MGB code, which is named after its original developers Mani, Gliebe and Balsa.<sup>30</sup> Over the years, it has been shown that the approximations employed in the MGB code are too restrictive and, as a result, a number of improved jet noise codes have been developed. These include the JeNo code,<sup>31</sup> Tam's model<sup>32</sup> and Morris' model.<sup>33</sup> The distinction amongst these codes lies in subtle, but important, differences in the modeling and interpretation of the aerodynamic sound source. When high-fidelity CFD is used to model the source, often reasonably accurate predictions are obtained using these methods. As an example, measured and predicted spectra for a single flow, subsonic, round jet at two farfield angles (relative to the engine inlet axis) are shown in Figure 9. The predictions include those from the JeNo code as well as a variant of the MGB code called MGBK.<sup>34</sup> The level of agreement between jet noise predictions and experimental data varies for more complex nozzle designs and is a current research topic. These methods generally apply when the jet exit velocity is subsonic relative to the ambient speed of sound. The methods for calculating noise from supersonic jets have not yet been developed to the same level of fidelity and utility as the ones for subsonic jets.

Over the past decade, significant progress has been made in applying CAA to jet noise prediction and, as in the case of fans, less is modeled a priori and more is computed directly. A host of methods<sup>35</sup> including URANS, LES and DNS have been used to compute the jet noise directly from the first principles. Of course, it will be some time before the CAA methods can routinely be used for design work. To put the scale of the challenge in perspective, the landmark DNS simulation by Freund<sup>36</sup> required a massively parallel computer running several months to compute the unsteady field for a jet at the Reynolds number of  $Re = 3500$ . By contrast, a realistic jet from a turbofan engine at takeoff has a Reynolds Number closer to  $10^7$ . Since the computational complexity (as measured by the number of grid points) is thought to be proportional to  $Re^{9/2}$ , much more powerful (and cost-effective) computers are needed for CAA to become a practical design tool. For now, CAA is principally a diagnostic tool to investigate the myriad of subtle physical processes that contribute to jet noise.

### **4.3 Core Noise (Compressor, Combustor and Turbine)**

Unlike the fan and jet components, the prediction tools for core noise are mostly empirical and are based on work that was done in the 1970's. This is mainly a reflection of the fact that for modern turbofans the dominant source are the fan and jet, and so they have historically received most of the development work. The most widely used tools today for predicting core noise are a collection of correlations for predicting compressor, combustor and turbine noise.<sup>16-17, 37-39</sup> The correlations are used with experimental data to fit the spectra in regions where the particular component is thought to dominate. Since the overall levels are below the fan and jet noise, only portions of the spectra can be matched, which makes this procedure difficult especially as the noise levels from other sources are similar and there are no distinguishing characteristics in the spectra. Source diagnostic tests are used to help isolate the sources and are the basis for many of the correlations available today. With the progress that has been made in developing noise reduction technologies for the fan and jet components, the core noise is beginning to receive more attention as the next obstacle to be tackled for designing quiet aircraft engines. It is likely that within the next decade, analytical as well as computational tools will be developed to help improve core noise prediction capability.

## **5 FURTHER READING**

For more information on aircraft and engine noise, there is an excellent reference available that was published originally by NASA in 1991 and has been published by Springer-Verlag in 1994.<sup>40</sup> Each noise source is explained in detail and a comprehensive list of references is available at the end of each chapter.

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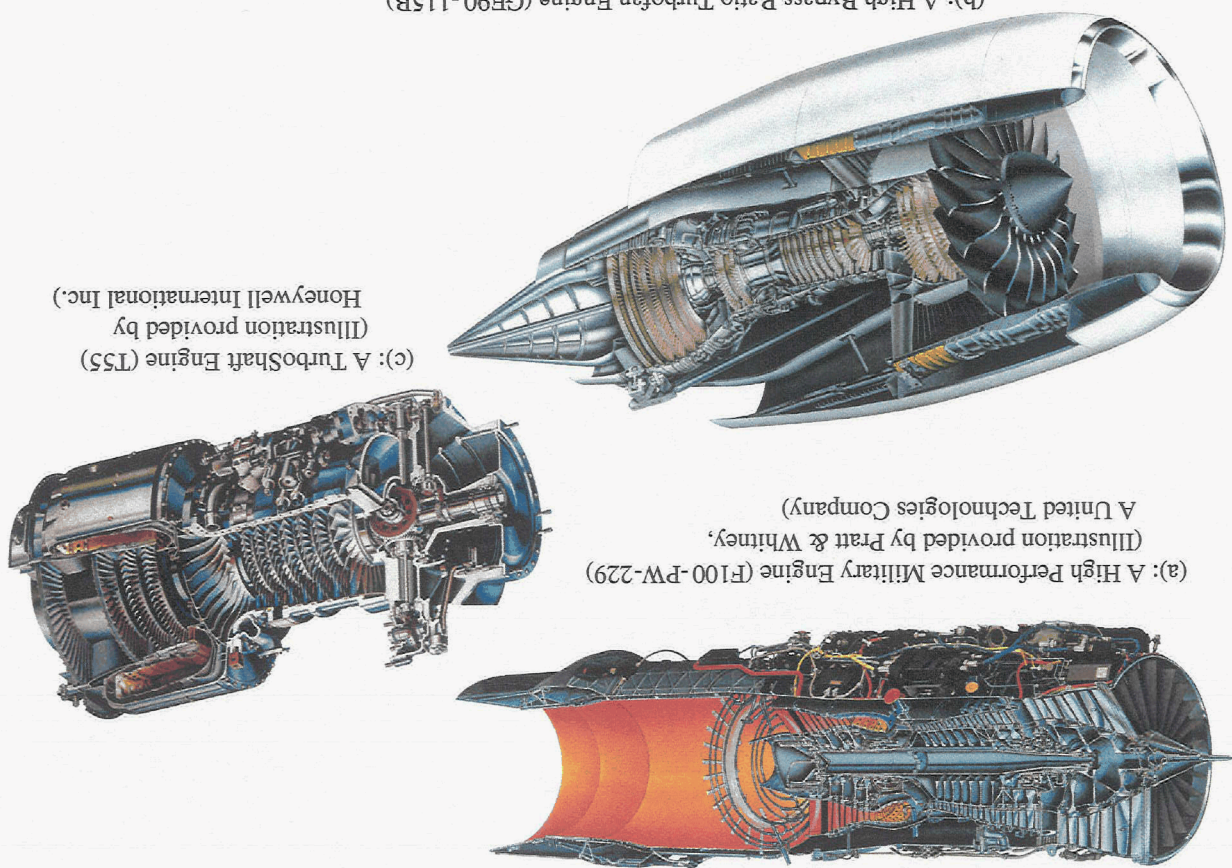


Figure 1. Various aircraft engine types.



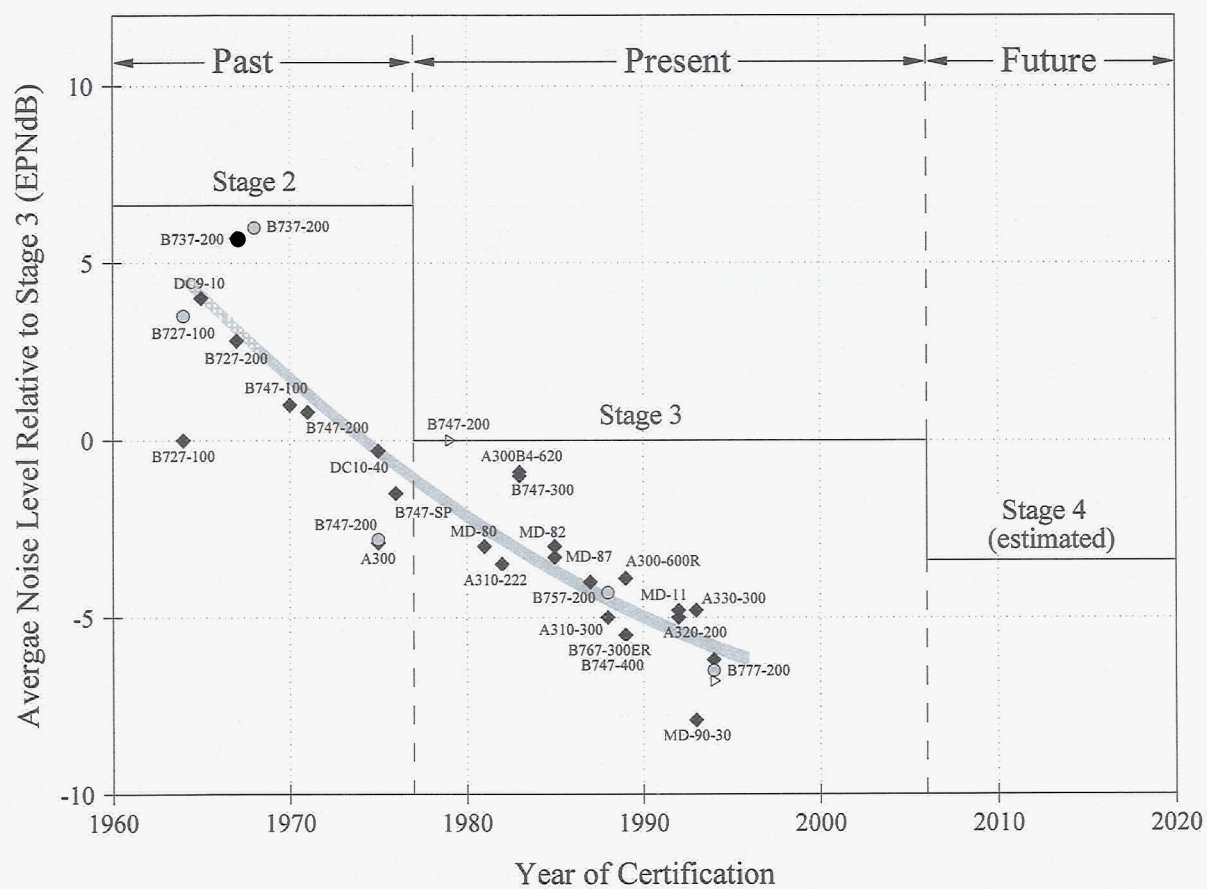


Figure 2. Evolution of aircraft noise reduction.

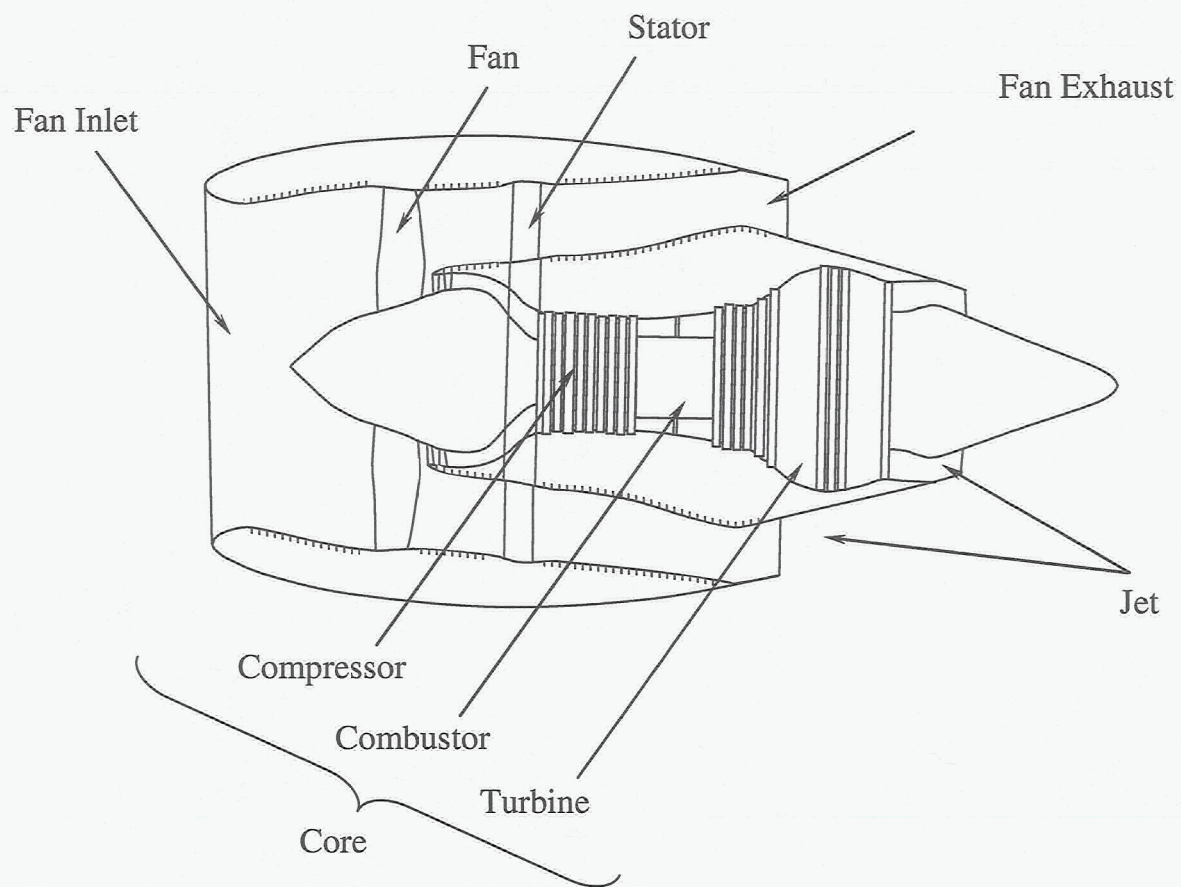


Figure 3. Dominant turbofan engine noise sources.

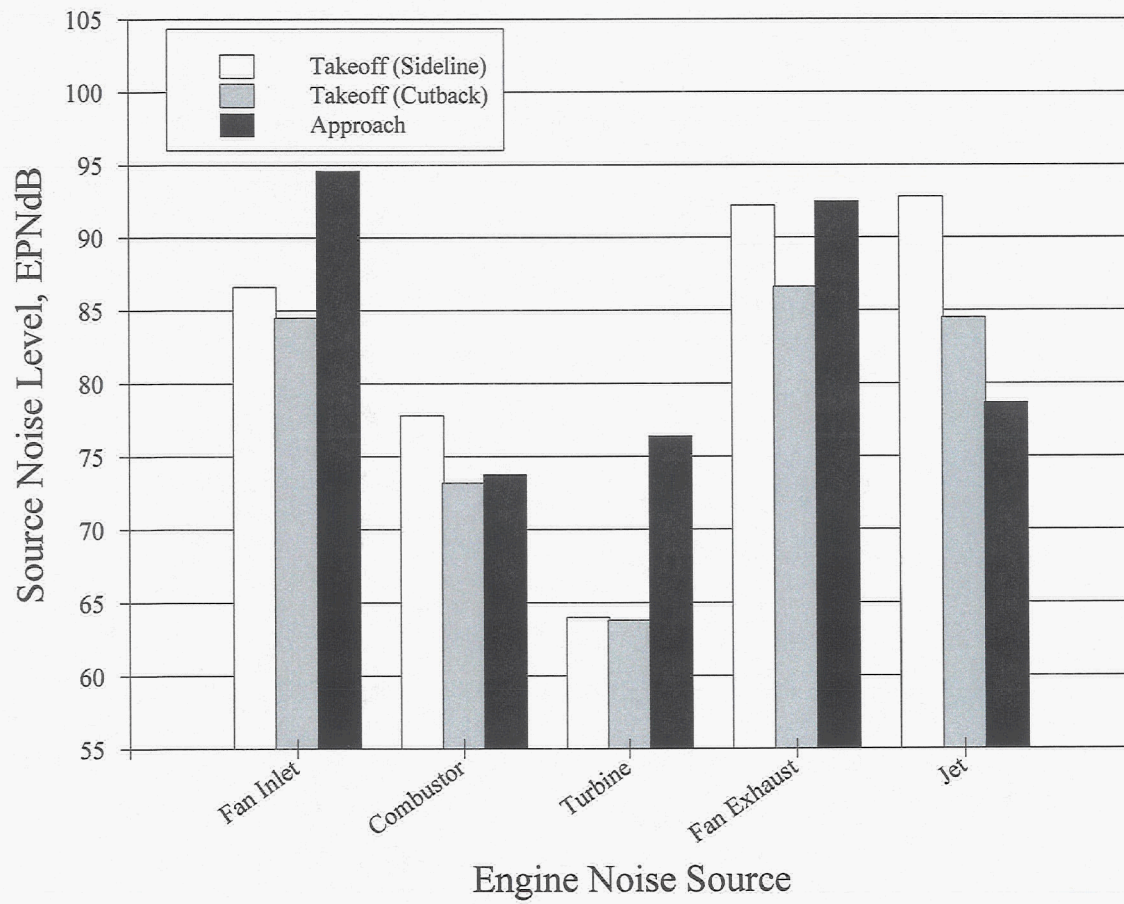


Figure 4. Typical engine noise levels.

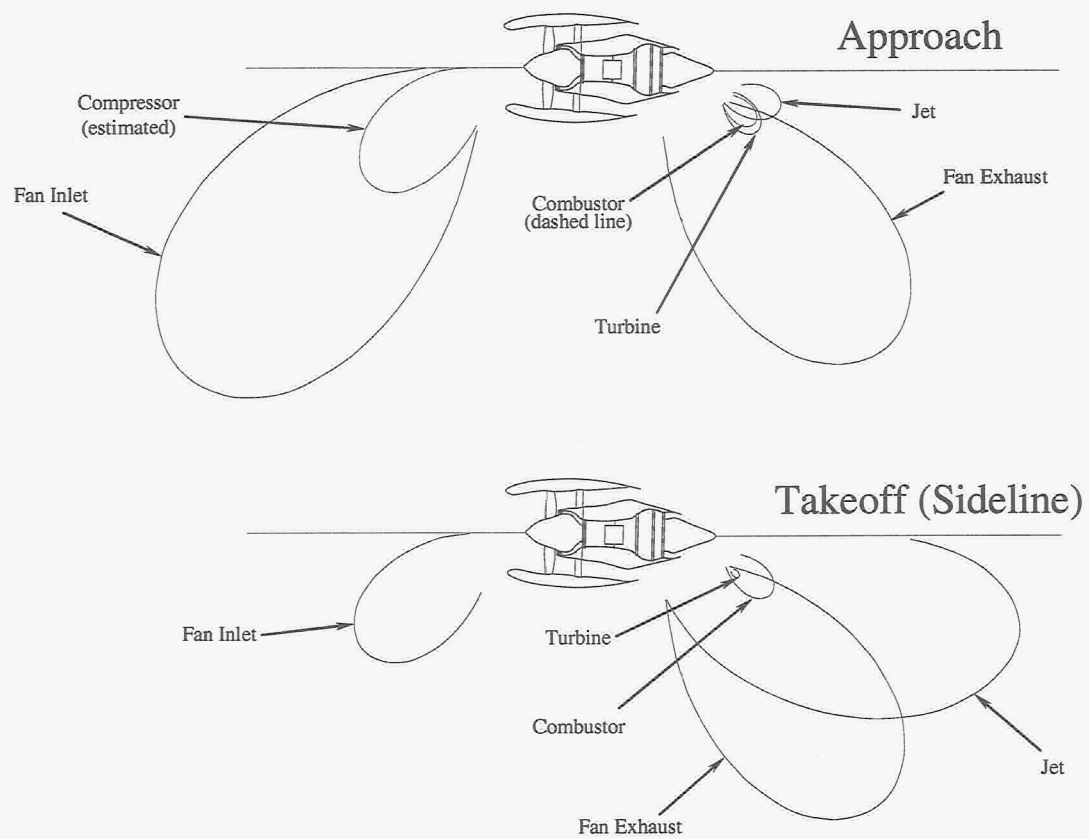


Figure 5. Typical noise radiation from turbofan engines.



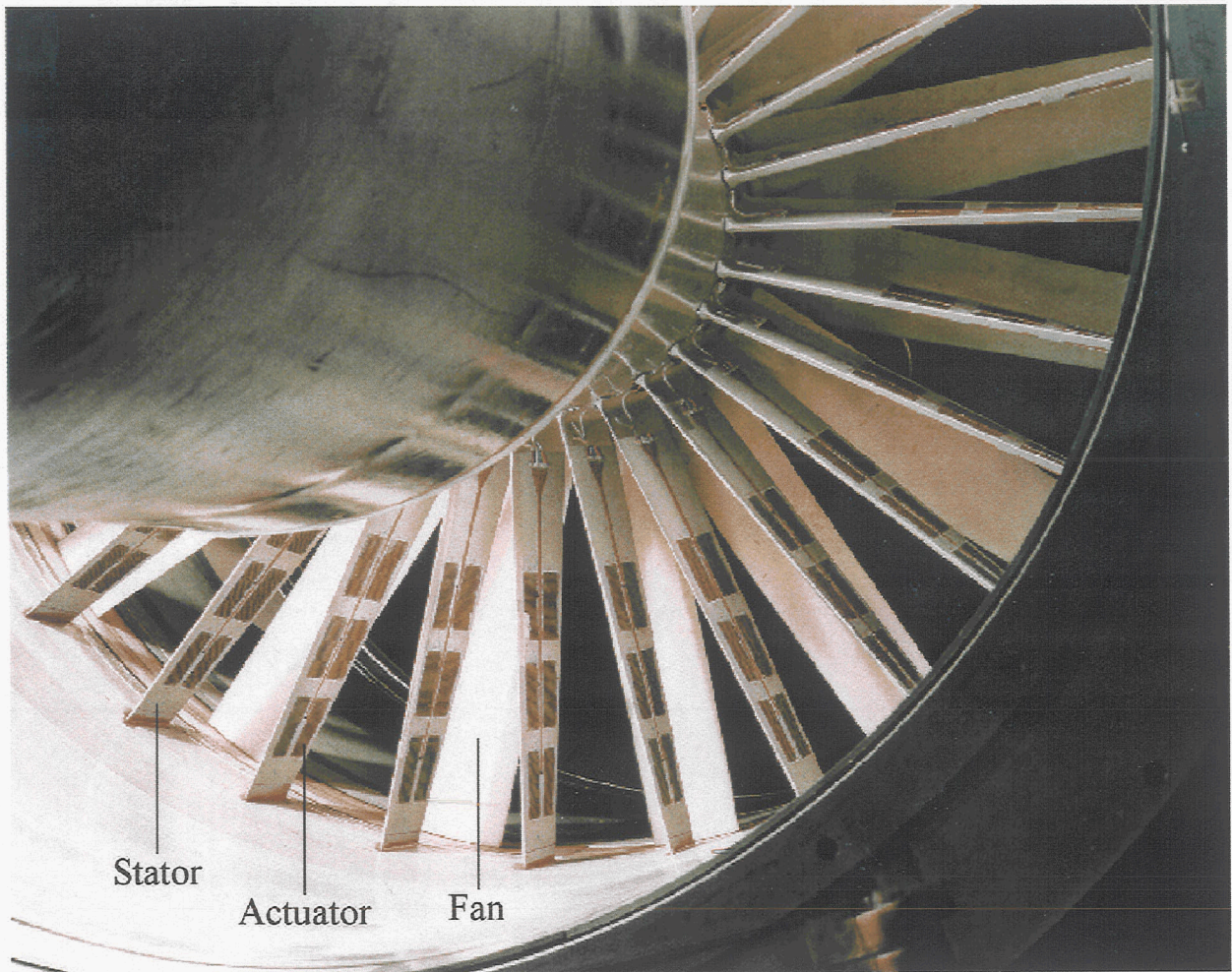


Figure 6. Active noise control for fan noise reduction.



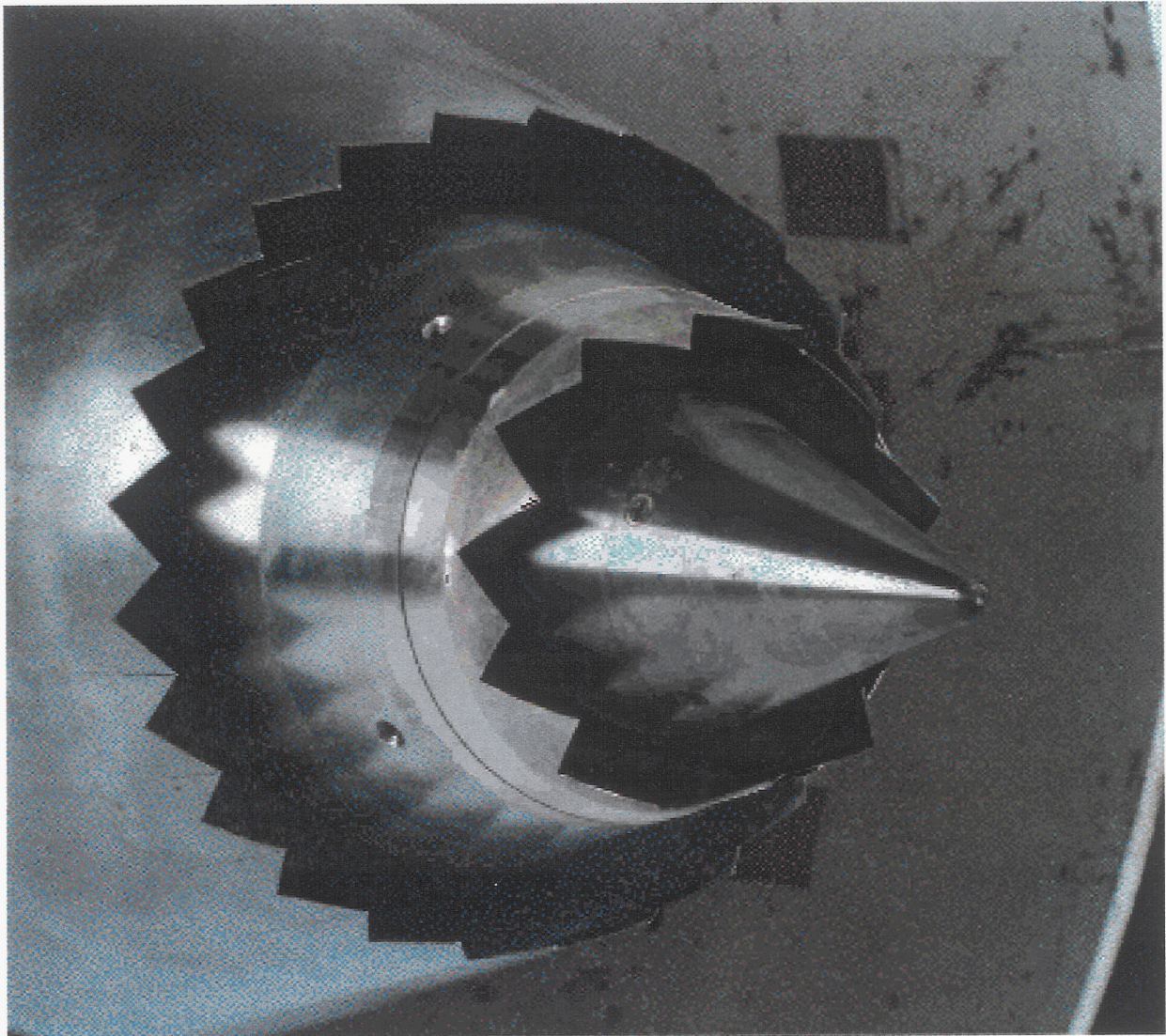


Figure 7. Chevron nozzle for jet noise reduction.



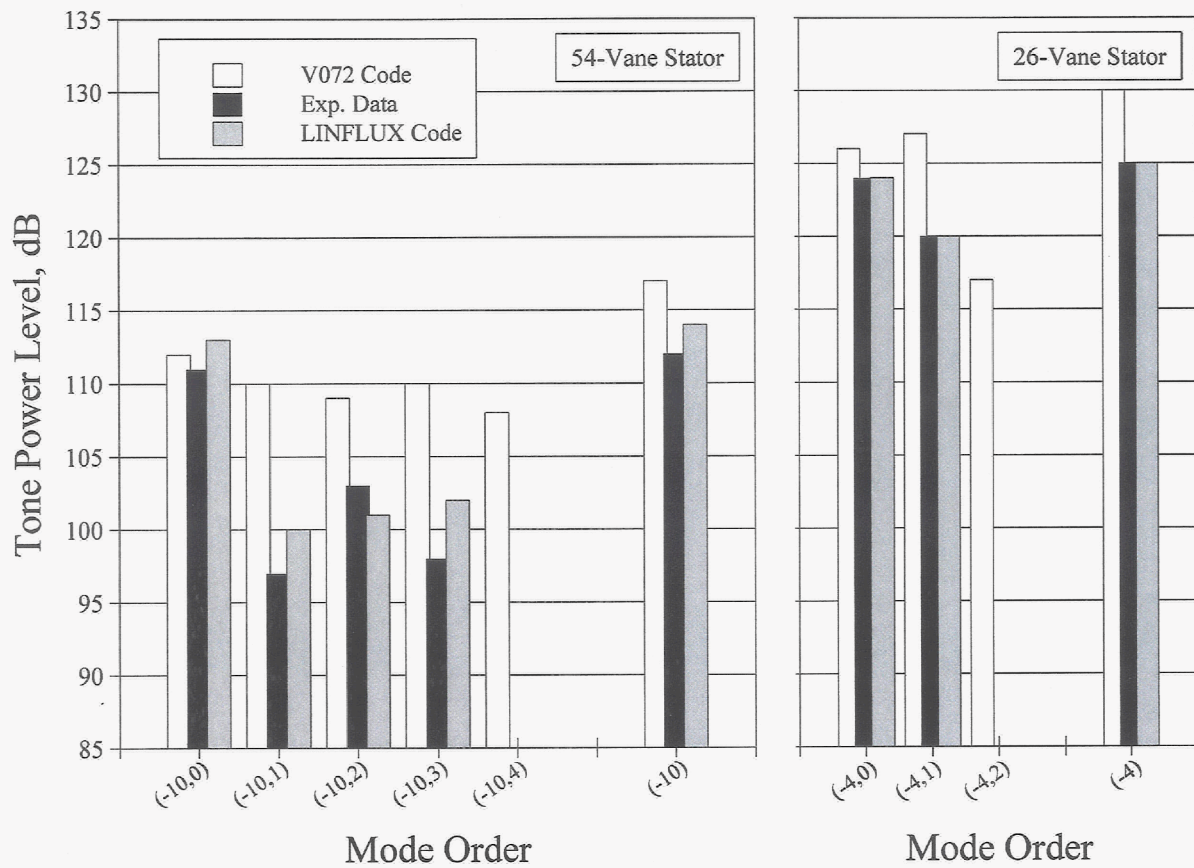


Figure 8. An example of fan tone noise prediction capability. Results shown are for rotor-stator interaction noise at a simulated approach condition.

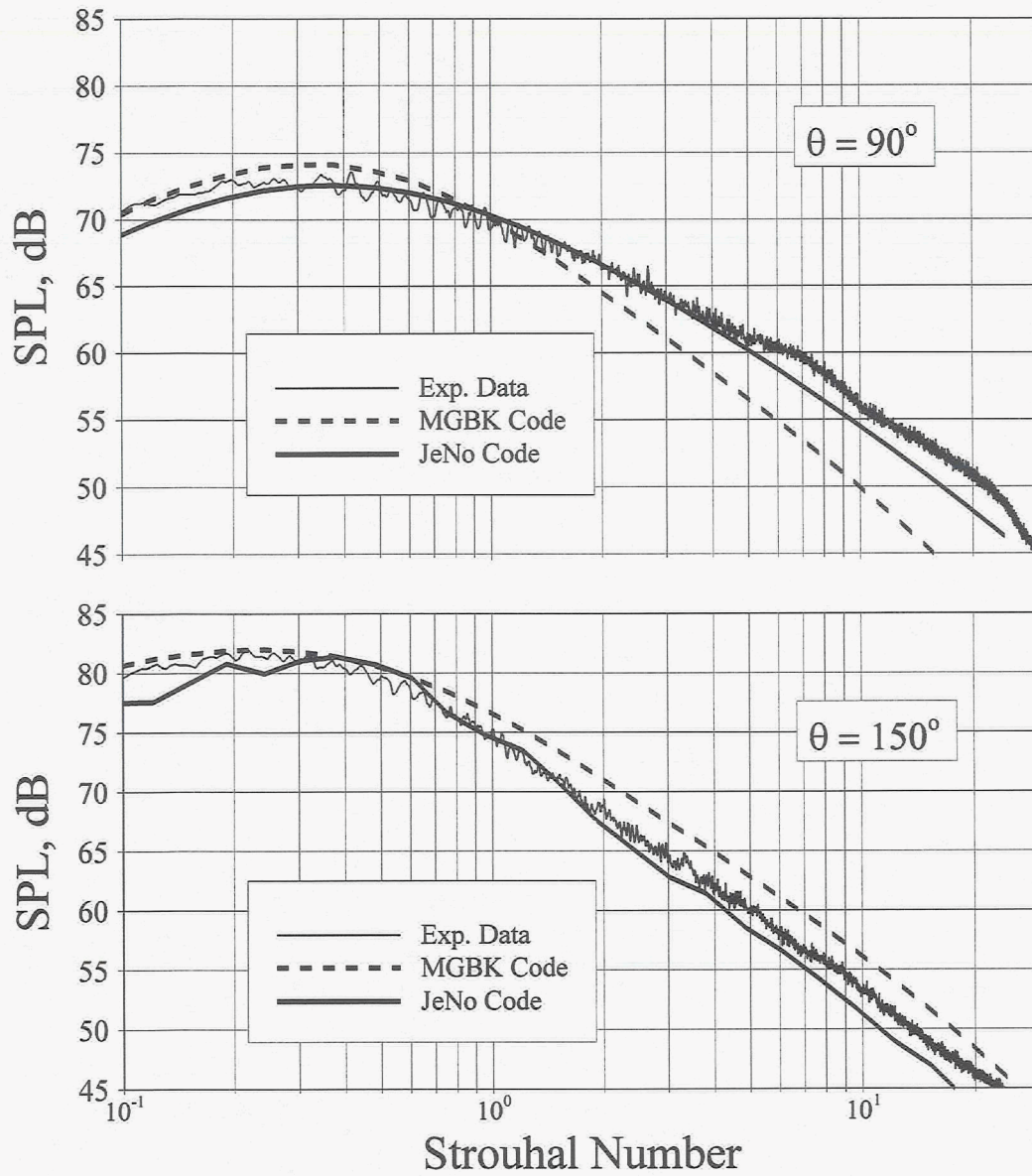


Figure 9. An example of jet noise prediction capability. Results shown are for a single flow, subsonic jet ( $M = 0.9$ ).